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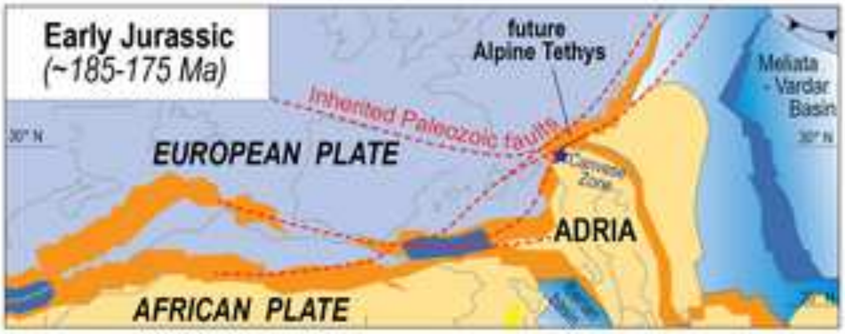
***Graphical Abstract**



Graphical Abstract - Festa et al_*Geoscience Frontiers (5x13 cm)*

*Manuscript

The role of structural inheritance in continental break-up and exhumation of Alpine Tethyan mantle (Canavese Zone, Western Alps)

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Abstract

The Canavese Zone (CZ) in the Western Alps represents the remnant of the distal passive margin of the Adria plate, which was stretched and thinned during the Jurassic opening of the Alpine Tethys. Through detailed geological mapping, stratigraphic and structural analyses, we document that continental break-up of Pangea and tectonic dismemberment of the Adria distal margin, up to mantle rocks exhumation and oceanization, did not simply result from the syn-rift Jurassic extension but was strongly favored by older structural inheritances (the Proto-Canavese Shear Zone), which controlled earlier lithospheric weakness. Our findings allowed to redefine in detail (*i*) the tectono-stratigraphic setting of the Variscan metamorphic basement and the Late Carboniferous to Early Cretaceous CZ succession, (*ii*) the role played by inherited Late Carboniferous to Early Triassic structures and (*iii*) the significance of the CZ in the geodynamic evolution of the Alpine Tethys. The large amount of extensional displacement and crustal thinning occurred during different pulses of Late Carboniferous – Early Triassic strike-slip tectonics is well-consistent with the role played by long-lived regional-scale wrench faults (e.g., the East-Variscan Shear Zone), and suggest a re-discussion of models of mantle exhumation driven by low-angle detachment faults as unique efficient mechanism in stretching and thinning continental crust.

Key Words

Alpine Tethys, Western Alps, Jurassic ophiolite, structural inheritance, continental break-up, mantle exhumation

1. Introduction

During last decades a large interest has been dedicated in literature to processes and mechanisms of continental break up, mantle exhumation and sea-floor spreading related to the Jurassic rifting of the Alpine Tethys (i.e., the Ligurian – Piedmont Ocean). Comparison with present-day settings (e.g., Atlantic Ocean, see Contrucci et al., 2004; Moulin et al., 2005; Red Sea, see Cochran and Karner, 2007; Norway passive margin, see Osmundsen and Ebbing, 2008) allowed to develop different modes of progressive stretching and lithospheric thinning, which may drive the sharp decrease in crustal thickness and strong decoupling between upper crust and continental mantle, up to continental breakup and mantle exhumation (e.g., Brun and Beslier, 1996; Péron-Pindvidic et al., 2007; Ranero and Pérez-Guissinyé, 2010; Clerc et al., 2018 and reference therein). These models were subsequently applied in different exhumed orogenic belts throughout the world as, for example, in the Alps (Froitzheim and Eberli, 1990; Manatschal et al., 2001; Manatschal, 2004; Mohn et al., 2010; Beltrando et al., 2012; Masini et al., 2012 and reference therein), Pyrenees (e.g., Clerc et al., 2012; Clerc and Lagabrielle, 2014), and Betics (e.g., Frasca et al., 2016), independently by the structural and metamorphic complexities and polyphasic deformation of these regions. Here, less attention has been devoted to the potential role played by pre-Jurassic structural inheritance, which may have significantly controlled the location and kinematics of the Alpine Tethys rifting and mechanisms of mantle exhumation.

Structural inheritance may produce lateral variations in crustal thickness and thus in the rheology of both the continental crust and upper mantle lithosphere (e.g., Armitage et al., 2010; Aulin et al., 2013; Spalla et al., 2014; Phillips et al., 2016; von Raumer et al., 2016; Fazlikhani et al., 2017; Marotta et al., 2018; Will and Frimmel, 2018). Multiple rifting events may have the same or different kinematics (e.g., Talwani and Eldholm, 1972; Armitage et al., 2010) and, the rift trend may be inherited from a previous orthogonal rift stage (e.g., Bonini et al., 1997; Wolfeden et al., 2004) or develop as the result of both specific far-field stresses and local weakness (Bellahsen et al., 2006) in the specific case of oblique rifting. Particularly, oblique extension may significantly facilitate the rifting process and mantle exhumation, as oblique deformation requires less force in order to reach the plastic yield limit than rift-perpendicular extension (Brune et al., 2012; Autin et al., 2013). However, although a general agreement exists among geoscientists on the important role of structural inheritance in influencing and controlling the architecture and structural evolution of rifted margins, other studies suggest that this role is most of the time local and unable to explain the non-coincidence of early rifting stages and location of the final breakup (e.g., Dunbar and Sawyer, 1989; Bertotti et al., 1993; Direen et al., 2008; Lundin and Doré, 2011; Manatschal et al., 2015 and reference therein).

Discrimination on the role played by structural inheritances controlling the tectonic evolution and structural deformation pattern of lithosphere and the onset of rifting stage is particular difficult to decipher in orogenic belts. In fact, during their polyphasic tectonic and/or tectono-metamorphic evolution, structural inheritances may be commonly (i) repeated reactivated (e.g., Spalla et al., 2014; Ballèvre et al., 2018; Balestro et al., 2018), and/or (ii) masked by thick sedimentary and/or magmatic sequences that also prevent detailed observation on the pre-rift crustal architecture (Ballèvre et al., 2018).

In this paper, we document through multiscale, field- and laboratory- based structural studies (from geological map scale to mesoscale and scanning electron microscope – SEM – scale), and re-definition of the stratigraphic succession, the internal architecture, tectono-stratigraphic setting and geological evolution of the Canavese Zone (CZ hereafter) in the Internal Western Alps (Figs. 1A and 1B), which represents the remnant of the Jurassic syn-rift stretching, thinning and dismemberment of the distal passive margin of Adria, occurred during the opening of the Alpine Tethys (e.g., Elter et al., 1966; Bertotti et al., 1993; Ferrando et al., 2004 and reference therein). Particularly, we document that the Jurassic continental break-up and tectonic dismemberment of the distal margin of Adria, up to mantle rocks exhumation, did not simply result from the syn-rift Jurassic extension but was strongly favored by older structural inheritances (Variscan to Early Triassic), which controlled earlier lithospheric weakness. Importantly, our findings are strongly constrained on a new geological map at 1:5.000 scale of the entire CZ, a sector in which official geological maps were older than one century of years (see Franchi et al., 1912).

2. Regional Geological Setting

The Canavese Zone (Argand, 1909) is discontinuously exposed in the Internal Western Alps (Figs. 1A and 1B), where it consists of a narrow zone, few kilometers wide and about 40 km long, bounded by two regional-scale first-order faults, about NE-striking, known as the Internal and External Canavese Lines (see Biino and Compagnoni, 1989). The Internal Canavese Line corresponds to an older left-lateral mylonitic contact (Late Cretaceous, Schmid et al., 1987; Biino and Compagnoni, 1989), developed during low-grade Alpine metamorphism (i.e., prehnite–pumpellyte facies conditions; Biino and Compagnoni, 1989; Borghi et al., 1996), which separates the CZ form the Ivrea - Verbano Zone of the S- and SE-verging Southern Alpine Domain (Fig. 1B) (see Dal Piaz et al., 2003; Schmidt et al., 2004). The External Canavese Line (Biino and Compagnoni, 1989), which developed in Oligocene – Early Miocene time (e.g., Lanza, 1984; Biino and Compagnoni, 1989; Berger et al., 2012) under brittle conditions, corresponds to the southwestern prolongation of the Insubric Line or Peri-Adriatic Line (Schmidt et al., 1987), separating to NW the CZ from the Austroalpine Sesia Zone (Fig. 1B) and related Tertiary volcano-sedimentary cover (Berger et al., 2012). The Ivrea – Verbano Zone corresponds to a section of Adriatic lower crust, which consists of upper amphibolite – to granulite facies metasediments (the Kinzigite Formation *Auct.*), with mafic and ultramafic bodies, which were intruded by Lower Permian gabbro and diorite (the Mafic Complex *Auct.*; see Zingg et al., 1990; Quick et al., 2003). It is tectonically juxtaposed along the Cossato – Mergozzo – Brissago Line *Auct.*, to the Serie dei Laghi (Boriani and Sacchi, 1974; Mulch et al., 2002), consisting of two composite Variscan basement units (Strona Ceneri monometamorphic Unit and Scisti dei Laghi polymetamorphic Unit *Auct.*), which are separated by a horizon of amphibolites with lenses of ultramafic rocks called the Strona-Ceneri Border Zone (Giobbi Mancini et al., 2003). The two Variscan basement units, consisting of metasediments and meta-intrusives, metamorphosed under amphibolite-facies conditions (Boriani et al., 1990), were both intruded by Lower Permian granitoids, and covered by volcanic rocks and Permian to Cretaceous sediments (Bertotti et al., 1993; Boriani and Origoni Giobbi, 2004; Quick et al., 2009).The Sesia Zone, which is part of the NW-verging Alpine axial belt (i.e., the Austroalpine Sesia-Dent Blanche nappes and the Penninic Domain), represents a composite unit of Adriatic continental crust, which was metamorphosed under blueschist- to eclogite facies conditions during the early building of the Alpine orogeny (e.g., Spalla et al., 1991; Manzotti et al., 2014; Giuntoli and Engi, 2016 and reference therein).

The CZ, throughout its southern, central and northern sectors, is commonly described as consisting of a Variscan basement, Lower Permian igneous bodies and Permian to Lower Cretaceous pre-rift, syn-rift ad post-rift sediments. The former has been distinguished into lower and upper crustal rocks (see Ferrando et al., 2004). Lower crustal rocks, occurring in the Southern and Central sectors of the CZ (SCZ and CCZ hereafter, respectively), consist of migmatites intruded by anatectic leucogranite with enclaves of mafic granulite (e.g., Baggio, 1965b; Wozniak, 1977; Ferrando et al., 2004) of Ivrea – Verbano Zone affinity. The upper crustal rocks consist of amphibolite-facies ortogneiss, micaschist and amphibolite, occurring in the CCZ (see Wozniak, 1977; Borghi et al., 1996; Ferrando et al., 2004), and of greenschist-facies paragneiss, ortogneiss, phyllite and metabasite, occurring in the northern sector of the CZ (NCZ hereafter; see Biino and Compagnoni, 1989). These upper crustal rocks, likely of Strona Ceneri Zone affinity (Borghi et al., 1996; Sacchi et al., 2007), were intruded by Lower Permian granitoids at shallow crustal levels (see Ferrando et al., 2004). Lenticular-shaped slices of serpentinized peridotite locally occur in the SCZ (Levone area, e.g., Novarese, 1929; Baggio, 1965a; Elter et al., 1966; Ahrentd, 1972; Wozniak, 1977; Barnes et al., 2014).

The Variscan basement is overlain by Lower Permian volcanics and volcanoclastics (Fenoglio, 1931; Baggio, 1963a, 1965a, 1965b; Sturani, 1964; Elter et al., 1966; Ahrendt, 1972; Wozniak, 1977; Biino and Compagnoni, 1989; Borghi et al., 1996; Ferrando et al., 2004), followed by pre-rift sediments of Permian to Triassic age (Verrucano *Auct.* and Middle Triassic dolostone; see Elter et al., 1966; Ferrando et al., 2004; Berra et al., 2009) and by Lower- to Middle Jurassic syn-rift sediments (“Macchia vecchia”, “Polymictic breccias”, “Levone breccias”; see Elter et al., 1966; Ferrando et al., 2004). The CZ sedimentary succession ends with a post-rift succession, Middle Jurassic to Early Cretaceous in age, consisting of Radiolarites (Middle – Late Jurassic), Maiolica micritic limestones (late Tithonian – Berriasian, see Baggio, 1963b), and Palombini shale (Early Cretaceous, see Baggio, 1965a; Elter et al., 1966). The entire Canavese succession is overprinted by Alpine metamorphism, which is limited to the anchizone and dated to 60-71,8 Ma (Zingg et al., 1976).

Although primary relationships between the different terms of the Variscan basement and related sedimentary-volcanic cover succession are strongly complicated by Alpine deformation and faulting (e.g., Ahrentd, 1972; Wozniak, 1977; Biino and Comapagnoni, 1989; Borghi et al., 1996; Ferrando et al., 2004), low-angle detachment faults of Jurassic age were postulated to explain the juxtaposition of lower and upper crustal rocks and the mantle exhumation in the CCZ (Ferrando et al., 2014) and SCZ (Barnes et al., 2014), respectively. This deformation would have accompanied the evolution of the Ocean-Continental Transition zone (OCT) between the “hyperextended” passive margin of Adria and the Ligurian – Piedmont Ocean (Alpine Tethys). However, contrasting interpretations on the stratigraphic (e.g., Barnes et al., 2014 and reference therein) or tectonic (e.g., Novarese, 1929; Baggio, 1965a; Elter et al., 1966; Sturani, 1973) nature of the contact between Middle - Upper Jurassic (post-rift) radiolarian cherts and serpentinized peridotites in the SCZ (Levone area) were differently proposed to support mechanisms of mantle exhumation through Jurassic (syn-rift) low-angle detachment faults or Alpine to neo-Alpine related tectonic slicing (see, e.g., Elter et al., 1966 for a complete discussion).

3. The Canavese Zone stratigraphy revisited

Detailed geological mapping and stratigraphic and structural analysis, allowed to revisit the tectonically disrupted succession of the CZ (Fig. 2A), which consists of small slivers of serpentinized peridotites, a Variscan metamorphic basement, bodies of post-Variscan intrusives and an Upper Carboniferous to Lower Cretaceous cover succession.

3.1. Mantle rocks

Slices of upper mantle rocks, limited to the SCZ (Fig. 2A), consist of massive serpentinite, passing to sheared ones close to fault contacts (Fig. 3A). The serpentinite is composed by Cr-serpentine and fine-grained magnetite, and by overprinted Cr-andradite and tremolite. The pre-serpentinization mineral assemblage is preserved as relics of clinopyroxene porphyroclasts, and as mesh textures. The massive serpentinite is crosscut by pyroxenite dykes, centimeters to decimeters in thickness, which mainly consist of clinopyroxene partly overprinted by epidote and Mg-chlorite.

Major and trace element geochemistry is consistent with small to moderate mantle depletion of sub-continental mantle rocks, while oxygen isotope data ($\delta^{18}O$ values: from +5.2 to +6.8), support low-temperature serpentinization (150° - 200°C) by sea-water at or near the seafloor (Barnes et al., 2014).

3.2. The Variscan metamorphic basement

The characteristics of the Variscan basement can be defined in detail in the CCZ (Bric Figlia area; Figs. 2A), wherein a poorly disrupted lithostratigraphic succession is exposed. It consists of two tectonically superposed units (Lower and Upper units), which show different lithostratigraphic successions and are separated by a discontinuous horizon of amphibolite (Figs. 4A, 4B and 4C). The two units were both metamorphosed under amphibolite-facies conditions during Variscan orogeny.

The Lower Metamorphic Unit (LMU hereafter) consists of medium- to coarse-grained orthogneiss, tens to several hundreds of meters thick, deriving from pre-Variscan granitod as shown by the homogeneous structure with cm-sized porphyroclasts of K-feldspar and by the occurrence of layers of aplitic composition, centimeters in thickness. The orthogneiss (Fig. 3C) consists of altered plagioclase of oligoclase composition, quartz in plurimillimetric grains, K-feldspar in altered idiomorphic crystals and annitic-rich red biotite. Minor white mica, Fe-Mg chlorite and Fe-epidote also occur, together with rutile, apatite and association of zircon, monazite and allanite, as accessory minerals. The Variscan foliation is pervasive and mainly defined by the preferred orientation of biotite and of quartz-plagioclase aggregates. The Variscan mineral assemblage is partly overprinted by pluri-centimeters granoblastic domains, consisting of (*i*) K-feldspar with myrmekite intergrowth, (*ii*) polygonal quartz and (*iii*) idiomorphic oligoclase-andesine plagioclase with antiperthite intergrowth of K-feldspar, and by non-oriented idiomorphic to allotriomorphic crystals of biotite, garnet and white mica. Fibrous sillimanite and idiomorphic pseudomorph of white mica after cordierite, also occur. These post-Variscan MT-HT minerals and fabrics highlight that the orthogneiss was partly transformed into migmatitic gneiss (Fig. 3B). The latter is also characterized by occurrences of garnet-rich restite and is associated with coarse-grained white mica-bearing leucogranite of anatectic origin (see also Ferrando et al., 2004). The migmatitic gneiss and leucogranite are spatially associated with intrusions of post-Variscan gabbro and diorite (Fig. 3B; see below).

The ortogneiss partly transformed into migmatitic gneiss and with associated leucogranite, also occur in the SCZ (Levone area; Fig. 2A), wherein they are tectonically juxtaposed to the above described mantle rocks through an Alpine faults.

The orthogneiss are embedded and/or passes upward to fine-grained micaschist and medium-grained paragneiss, which show a maximum thickness of about few hundreds of meters (Figs. 4A, 4B and 4C). The micaschist mainly consists of quartz, white mica, biotite locally associated with minor graphite, zoned garnet in millimeters wide porphyroblasts, plagioclase and chlorite. Similarly, the paragneiss consists of quartz, biotite, garnet and plagioclase, with minor K-feldspar. Zircon, apatite, rutile and titanite occur as accessory minerals both in the micaschist and paragneiss. The Variscan foliation is pervasive and is mainly defined by oriented white mica and biotite. The

Variscan mineral assemblage is locally overprinted by idiomorphic to allotriomorphic biotite and garnet, which statically grown during the post-Variscan MT-HT heating event. Unlike the orthogneiss, the metasediments of the LMU were not transformed into migmatites.

The LMU and the overlying Upper Metamorphic Unit (UMU hereafter) are separated by a discontinuous horizon, up to ten meters thick, of amphibolite (Figs. 3D, 4A and 4B). The latter mainly consists of amphibole of tschermakitic-pargasitic composition, occurring both in oriented lepidoblasts and in large crystal relics, and of plagioclase of oligoclase composition, occurring both in idiomorphic porphiroclasts and altered porphiroblasts. The Variscan mineral assemblage also consists of titanite, rutile, apatite, zircon and epidote. The magmatic origin of the amphibolite is suggested by the large idiomorphic crystal relics of amphibole and it likely derives from pre-Variscan effusive rocks of basaltic composition.

The UMU of the Variscan basement consists of alternating medium-grained metasandstone and fine-grained metasiltstone (Figs., 3E, 4A and 4B), up to tens of meters thick, which are characterized by preserved sedimentary organization in fining-upward horizons. These metasediments are locally interbedded with leucogneiss and fine-grained gneiss. The metasandstone and metasiltstone consist of oriented plagioclase blasts of oligoclase composition, irregular to lobate oriented quartz grains, red biotite, and minor white mica lamellae and garnet peciloblasts. The leucogneiss consists of meters-thick horizons made up of quartz, K-feldspar porphiroclasts, rounded granoblast of plagioclase, white mica, with minor biotite and rare garnet. Zircon, apatite and titanite occur as accessory minerals. The fine- to medium-grained texture and the fabric characterized by alternating white mica- and quartz-feldspathic -rich layers, millimeters to centimeters thick, suggest a volcanoclastic protolith of acidic composition. Boudins and decimeters thick levels of fine-grained gneiss of mafic composition also occur within the metasandstone, and consist amphibole, biotite, plagioclase and minor quartz.

The basement exposed in the NCZ (Lessolo and Montalto areas) is stratigraphically quite similar to the UMU, but it was metamorphosed under greenschist-facies metamorphic conditions during the Variscan orogeny (see Biino and Compagnoni, 1989, and Borghi et al., 1996).

3.3. The post-Variscan intrusives

In the whole CZ (Fig. 2A), the Variscan metamorphic basement was intruded by plutonic rocks and hypoabissal dykes, and capped by volcanic rocks. Plutonic rocks are represented by a magmatic suite consisting of up to 10 m sized bodies of gabbro, up to hundreds of meters wide bodies of diorite and tonalite, and kilometers sized granite plutons. The gabbro intruded rocks of the LMU in the SCZ (Courgnè area; see Biino et al., 1986) and in the CCZ (Vidracco area), and it mainly consists of plagioclase, clinopyroxene and amphibole. The diorite and associated quartz-bearing diorite, intruded rocks of the LMU in the CCZ (Fig. 3B) and rocks of the UMU in the NCZ, and are composed of plagioclase, biotite, amphibole and clinopyroxene, whereas the tonalite occurs in the CCZ and consists of plagioclase, quartz, K-feldspar and biotite. The whitish to pinkish granite intruded rocks of the LMU and UMU, and consists of K-feldspar, quartz, plagioclase and biotite, and locally shows diorite enclaves. The granite also occurs as dykes within the diorite (Fig. 3F). Plutonic rocks also consists of coarse-grained white mica-bearing leucogranite. The latter occurs as centimeters sized pods, decimeters wide dykes and tens of meters sized irregular masses, which intruded the migmatitized orthogneiss as well as already cooled diorite. The leucogranite resulted from partial melting of the orthogneiss and its composition is similar to that of the quartz-feldspathic granoblastic domains overprinting the Variscan mineral assemblage in the orthogneiss. The hypoabissal dykes, up to decimeters wide, are widespread in the CCZ wherein intruded the granite and the whole Variscan metamorphic basement (Fig. 2A), highlighting that both the LMU and UMU, at time of dykes intrusion, were already exhumed at shallow crustal levels. They correspond to fine grained lamprophyre, dolerite and porphyry, mainly made up of plagioclase, biotite and amphibole, and to granophyre consisting of plagioclase, K-feldspar, quartz and biotite.

3.4. The Upper Carboniferous – Middle Triassic pre-extensional succession

Above a stratigraphic unconformity, which corresponds to the "Hercinian unconformity" *Auct.*, this succession shows significant lateral and vertical variations in both facies and thickness (Figs. 2A, 4A, 4B and 4C). The lower term corresponds to discontinuous continental fluvial deposits, up to few tens of meters in thickness, and consisting of clast- to matrix-supported conglomerates and coarse-grained sandstones (Fig. 3G). Clasts, rounded to irregular and up to decimeters in size, consist of metasandstone, micascist, gneiss and fragments of quartz veins. These clasts likely sourced from the UMU, which is the Unit unconformably covered by this fluvial deposit. The matrix, which lacks of any volcanic material, ranges from siltite to fine-to coarse-grained arenite and shows a very scarce maturity with angular shaped lithics of the same composition of clasts. This lithostratigraphic unit, occurring in the CCZ (Serra Alta; Figs. 2A and 3G) and never documented before, corresponds to the Upper Carboniferous – Lower Permian Basal Conglomerate *Auct.* of the Lombardian Basin (see, e.g., Cadel et al., 1996; Ronchi and Santi, 2003; Cassinis et al., 2012; Berra et al., 2016). Together with both the LMU and UMU of the Variscan basement, it is unconformably overlain by volcanic rocks and volcanoclastic deposits (Figs. 2A and 3H) comparable with part of the Lower Member of the Collio Formation *Auct.* (see, e.g., Cadel et al., 1996; Cassinis et al., 2012) of the Southern Alps, Early Permian in age. Volcanic rocks consist of microporphyric reddish and greenish fine-grained rhyolite and minor blackish pheno-andesite with local occurrence of clast-supported rhyolitc ignimbrites in decimeters thick bodies. The Collio Formation is characterized by significant and abrupt thickness variations (Fig. 2A), ranging from hundreds to tens, and up to zero meters across sectors tectonically juxtaposed along high-angle ENE- to NE-striking faults. Volcanoclastics rocks are commonly associated with the thicker portion of this succession (Fig. 2A), where they show wedge-like geometry that gradually pinches out laterally. They consist of angular clasts of both metamorphic and volcanic rocks, and fragments of glass, feldspar and biotite phenocrysts, embedded in a reddish to purple fine-to medium grained aphanitic matrix of the same composition with flame structures. Upwards, this succession shows a riodacitic composition, and is characterized by lenticular horizons, decimeters in thickness, with clasts and lithics of gneiss, metasandstone and volcanic rocks.

In the CCZ, lacustrine deposits, which consist of dark grayish thinly laminated siltite and claystone beds, close upwards the volcanic member of the Collio Formation, resting unconformably onto both the volcanic rocks and the Variscan metamorphic basement. Through an angular unconformity, the Collio Formation is discontinuously overlain by reddish fluvial deposits of the Upper Permian Verrucano (Figs. 2A and 3H), which consist of conglomerates and coarse-grained pebbly sandstones with local siltstone layers (Fig. 3I). Pebble conglomerates are made of up to centimeters in size clasts of granitoids, hypoabissal dykes, volcanic and volcanoclastic rocks, and metamorphic rocks sourced from both the LMU and UMU and the interposed mafic rocks (i.e., amphibolite, metasandstone, micaschist and orthogneiss). Single clasts of conglomerate, likely sourced from the Upper Carboniferous – Lower Permian Basal Conglomerate *Auct.*, also occur. Remarkably, some clasts of metasediments and of orthogneiss show occurrences of garnet statically overprinting the Variscan mineral assemblages and of myrmekite intergrowth. This would indicate a pre-Late Permian age of the post-Variscan MT-HT heating event.

As for the Collio Formation, the Verrucano shows significant thickness variations (from zero meters to about 100 m) in sectors juxtaposed along ENE- to NE-striking faults (Figs. 4). Where the Collio Formation is lacking, it directly overlies the Variscan metamorphic basement units and/or the Basal Conglomerate.

The Triassic deposits show the most complete succession in the CCZ. They start with non-mappable greenish coarse-grained quartz-arenite, similar to the Lower Triassic Servino Formation *Auct.* of the Lombardian Basin, passing upward to alternating black graphite-bearing clay-schist and gray metasandstone layers, up to few meters thick. These sediments are followed by massive dolomitic limestone and dolostone (Fig. 5A, San Salvatore Dolostone, see Elter et al., 1966; Ferrando et al., 2004) of Middle Triassic age (Ladinic, see Berra et al., 2009) that, in the NCZ and SCZ, are directly overlain onto the volcanic member of the Collio Formation and rocks of the LMU, respectively, through a depositional hiatus (see also Berra et al., 2009) corresponding to Early Triassic. The Triassic succession shows a maximum thickness of few tens of meters.

3.5. The Lower – Middle Jurassic syn-extensional succession

This Jurassic succession unconformably overlies all the above described lithostratigraphic sequence (Figs. 2A, 5A), marking a Late Triassic – Early Jurassic depositional hiatus (see, e.g., Berra et al., 2009). In the NCZ and CCZ, the top of platform dolostone is overlain by dolomitic breccias with a reddish matrix (Macchia Vecchia breccias type, see Baggio et al., 1965b; Bernoulli et al., 1990; Ferrando et al., 2004), which also fills Neptunian dykes and/or red and green arenaceous limestone, forming a Lower Sinemurian – Toarcian (?) condensed syn-extensional succession (Fig. 5A; see Sturani, 1963; Elter et al., 1966), related to the onset of the Jurassic rifting stage. This condensed succession, gradually opens far from platform deposits to form a complete syn-extensional succession, up to 80-100 m thick, here informally named Muriaglio Formation. It consists of four members with lateral and vertical facies variations throughout the CZ (Fig. 2A). The lower “Clastic Member” includes different types of matrix- to- clast-supported breccias whose components differ each other’s on the basis of the nature of the source area. In the CCZ, components consist of clast-to matrix-supported polymicitic breccias (Polymictic breccias of Ferrando et al., 2004), with mainly sub-angular clasts, cm- to dm in size, embedded in a medium- to coarse-grained yellowish to reddish matrix, which unconformably overlain the Verrucano conglomerates and the Variscan metamorphic basement (Fig. 5B). Clasts are made of both units of the Variscan metamorphic basement (e.g., orthogneiss, amphibolite and metasandstone), volcanics and granitoids, and very rare Triassic dolostone (see also Ferrando et al., 2004). In the SCZ (Levone area; see Baggio, 1965b; Elter et al., 1966; Ferrando et al., 2004), the Clastic Member differs on the larger amount of Triassic dolomitic clasts and is unconformable overlain onto orthogneiss, migmatitic gneiss and leucogranite (Fig. 5C). In the NCZ, this member is reduced to few meters (Fig. 5D), while it reaches up to 40-50 m in thickness in the rest of the CZ. The age of the Clastic Member is tentatively attributed to Toarcian and/or late Early-Middle Jurassic by comparison with the Saluver Formation of the Australpine Err Nappe (see Ferrando et al., 2004). In the entire CZ, this member of the Muriaglio Formation gradually passes upward to the Arenaceous Member (roughly corresponding to the “Arenarie Rosse” of Baggio,1965b; the “Grès volcanodétritiques” of Wozniak, 1977, and the “sandstone and black shale” of Ferrando et al., 2004), which consists of alternating pelite and sandstone interbedded by dark-reddish argillitic levels, millimeters in thickness, which increase in number and thickness upwards (Figs. 2A, 5E). It passes upward and laterally to the Siltitic-arenaceous Member (Figs. 2A, 5F), which consists of alternating pinkish marly limestones with crinoids fragments and greenish to reddish and yellowish sandstone, in cm-thick horizons, interbedded by black pelitic to fine-grained sandstone levels with sub-rounded clasts of yellowish quartz-rich arenite, centimeters in size. Only in the NCZ (Montalto Dora sector), the upper part of the Muriaglio Formation is characterized by the Limestone Member (corresponding to the Pistono Schist and Bio Schist *Auct.* of Biino and Compagnoni, 1989 and reference therein), which consists of alternating limestone and sandstone in decimeters thick beds (Figs. 2A, 5G). The age of the Muriaglio Formation, which shows gradual and abrupt changes of thickness and facies in SW-NE and NW-SE direction (i.e., parallel and across ENE-to NE-striking faults), respectively, is attributed to the upper part of Early Jurassic – Middle Jurassic (see Elter et al., 1966 and reference therein).

3.6. The Upper Jurassic – Lower Cretaceous post-extensional succession

In the CCZ and SCZ, the Jurassic syn-extensional succession is unconformably overlain by post-extensional deposits (Fig. 2A). They consist of reddish argillite, alternating with yellowish-greenish pelite in decimeters thick horizons (Fig. 5H), passing upward and laterally to alternating reddish to greenish radiolarian-bearing cherts and shale (i.e., Radiolarites *Auct.*; Fig. 5I), in meters thick packages. Locally, the basal part of radiolarian cherts is interbedded by cm-thick layers of lithic sandstone sourced from volcanic rocks and granitoids (see also Ferrando et al., 2004). This composite unit, up to 40 m in thickness, shows strong similarities with the Selcifero Lombardo Group of Southern Alps, and is attributed to Middle – Late Jurassic (see Elter et al., 1966; Wozniak, 1977; Ferrando et al., 2004). Only locally (central part of the CCZ), the Selcifero Lombardo is followed by Calpionella limestones (i.e., Maiolica of Baggio, 1963b) of Tithonian – Berriasian age, which locally directly overlie the Variscan metamorphic basement and post-Variscan intrusives (Fig. 2A). The Canavese succession is closed up by the Lower Cretaceous

Palombini shale (see Elter et al., 1966), which unconformably overlies the Variscan metamorphic basement and the Jurassic succession (Fig. 2A).

4. Structural setting and tectonic evolution

The CZ corresponds to a narrow and complex polyphasic strike-slip deformation zone about NE-striking (Fig. 2A), defined by the interlacing of high-angle and anastomized faults, ENE- to NE- and E-striking, which isolate lenticular tectonic slices juxtaposing the different terms of the Paleozoic – Mesozoic cover succession, the post-Variscan intrusives and the Variscan metamorphic basement. To SW, in the SCZ, the main fault systems are gradually rotated to NNE-trending. The crosscut relationships between the above described stratigraphic unconformities and mapped faults, allow us to distinguish the characteristics of deformation through time as in the following.

4.1. Variscan deformation

Both the units of the Variscan metamorphic basement and the interposed amphibolite are overprinted by the same amphibolite-facies Variscan foliation, which is parallel to the lithological contacts (Figs. 4A, 4B and 4C). In sectors (e.g., Bric Figlia in the CCZ, see Fig. 4a) escaped from Alpine-related NE-striking reorientation (see below), it shows a roughly NW-striking orientation and is almost NE dipping at medium angle (Fig. 4A). In the NCZ, the Variscan foliation shows similar geometrical characteristics, whereas in the SCZ it is almost N-striking and E-dipping. This foliation corresponds to the axial plane of isoclinal folds, which deformed a pre-existing early Variscan foliation rarely preserved as a relic at fold hinges. The main foliation and the lithological contacts within the basement are locally deformed by late Variscan open folds which roughly show E- and W-plunging fold axis and N-dipping axial planes (Fig. 4A).

The Hercynian unconformity constrains this deformation of the Variscan metamorphic basement before Late Carboniferous time (Fig. 4).

4.2. Late Carboniferous to Early Permian faults

The different thickness and distribution of volcanic and volcanoclastic rocks of the Collio Formation in sectors juxtaposed along ENE- to NE-striking faults, well-agree with a tectonically controlled deposition during Early Permian time (Figs. 4A-C). In fact, the wedge-shaped volcanoclastic deposits, which pinch out laterally far from the faults, mainly occur in association with tectonically lowered sectors (Figs. 4B-E). Fault surfaces, which escaped from later deformation, and are sealed by the deposition of the lacustrine deposits of the Collio Formation and/or by the Verrucano, show both cartographic transtensional right-lateral and left-lateral movements (Figs. 4A-E). The uppermost temporal constrain to this tectonics is represented by the unconformable overlain of the lacustrine deposits of the upper part of the Collio Formation and of the fluvial Verrucano deposits (Late Permian) onto both the thin and thick volcanic sequence of the Collio Formation, and the LMU and UMU (Figs. 4A-E). The evidence that the volcanic member of the Collio Formation is directly overlain onto both the basement units (Figs. 4A-E), which are in turn juxtaposed along ENE- to NE-striking faults, also suggests that this fault activity likely started in Late Carboniferous as documented by the deposition of the Basal Conglomerate. Evidences of Early to Middle Permian fault activity is also documented by deformation-controlled emplacement of leucogranite which filled NE-striking fractures and associated faults (Fig. 3B).

4.3. Late Permian – Early Triassic faults

As for the Collio Formation, the different thickness of Verrucano deposits across ENE- to NE-striking faults, indirectly suggests their local reactivation in Late Permian – Early Triassic time (Figs. 4B-E). These faults depict divergent flower structures with “tulip” type geometry within the Verrucano and older lithostratigraphic units (Figs. 4B-C, 5N), in agreement with the continuation of transtensional movements as also suggested by paleomagnetic data (see Robustelli et al., 2018). The unconformable deposition of the Lower(?) and Middle Triassic succession onto either the Verrucano deposits, the Collio Formation, the post-Variscan intrusives and the Variscan metamorphic basement, constrains this faulting stage to pre-Middle Triassic (Fig. 2A).

4.4. Late Triassic – Early Jurassic faults (the Rifting stage)

The occurrence of an heterogeneous Lower Jurassic syn-extensional succession throughout the CZ, unconformably overlying the previously deformed Variscan metamorphic basement and related Upper Carboniferous – Middle Triassic cover succession (Figs. 2A, 4A-E), clearly documents the onset of the continental break-up related to the rifting of the Alpine Tethys (see, e.g., Elter et al., 1966; Bertotti et al., 1993; Ferrando et al., 2004; Berra et al., 2009). The about SW-NE gradual change of thickness and facies of the syn-extensional succession in sectors bounded by ENE- to NE-striking faults, which in turn also crosscut WNW- to W-striking faults (Fig. 4A), suggests that the Jurassic extension roughly occurred along a roughly E-W direction (present-day coordinates). The abrupt change of thickness and facies of the same syn-extensional succession across the long-lived ENE- to NE-striking faults, additionally suggest their reactivation, likely with transtensional movements. Although kinematic indicators directly correlated with this tectonic stage are dubitatively preserved because of subsequent reactivation (see below), map evidences tentatively suggest left-lateral movements, as also documented by Handy et al. (1999) to the NE. WNW- to W-striking faults are mainly SW-dipping at high-angle (Fig. 4A), and locally, as in the NCZ, the Middle Triassic platform dolostone preserves remnants of primary Jurassic tectonic-morphologic scarps toward which the syn-extensional Muriaglio Formation pinches-out, according to extensional displacements (i.e., fault striations and slikenlines mainly show normal-right movements). In this case, the syn-extensional breccias which drape the tectonic-morphological scarps mainly consist of dolostone clasts, sourced from the uplifted platform deposits (see Fig. 5C). On the contrary, where the syn-extensional clastic member of the Muriaglio Formation is directly overlain onto the Variscan basement and/or the Paleozoic succession, clasts mainly consist of these metamorphic rocks and very rarely of dolostone, as in the CCZ and SCZ (see Fig. 5B). In only one case in the CCZ (Bric Figlia area), the Clastic Member of the Muriaglio Formation rests unconformably onto an extensionally sheared Verrucano horizon, few meters thick and tens of meters long (Figs. 4A-B). The latter, which is characterized by the strong elongation of clasts according to a roughly ENE-oriented extensional stretching direction, is laterally bounded by NE-striking faults, close to which it is gradually reoriented. No other extensional low-angle shear zones, comparable with the above described one, have been observed in the CZ. The maximum vertical displacement of both these two main fault systems is of about few tens of meters (see Figs. 4B-E) as documented by the maximum thickness of syn-extensional deposits below the uncoformable deposition of the post-extensional Selcifero Lombardo, Early – Middle Jurassic in age. The latter, represents the uppermost temporal constrain to this deformation.

4.5. Late Cretaceous – Early Miocene deformation (Alpine stage)

The Alpine-related deformation is documented by different types of brittle to ductile structures, which show different expression according to the rock rheology and distance from the Internal and External Canavese Lines, about NE-striking (Fig. 2B). Although out of the aim of this paper we shortly describe the characteristics of this deformation in that it is useful to discriminate the contribute played by older tectonic deformation. Close to these faults, the interlacing of anastomosing transpressional left-lateral faults, ENE- and NE-striking (Fig. 2B), defines a shear zone, hundreds of meters wide, along which several lenticular tectonic slices are juxtaposed, depicting flower structures at different scales in section. A pervasive cleavage oriented parallel to these faults and overprinted stratigraphic boundaries, according to simple shear deformational mechanisms. Tight to open folds with NE and SW-plunging axis also occur (Fig. 4A). In the NCZ, this deformation is close associated with mylonitic deformation, which juxtaposed the Limestone Member of the Muriaglio Formation with the gabbros of the Ivrea - Verbano Zone (Fig. 5L; see, Biino and Compagnoni, 1989 for major details). Far from both the Internal and External Canavese Lines, the cleavage, which occurs as spaced surfaces ENE- to NE-striking, cuts at high angle the stratigraphic contacts according with pure shear deformation mechanisms. Kinematic indicators on ENE- to NE- and W- to WNW-striking faults, are consistent with a roughly NNE-oriented shortening direction (Fig. 2B), indicating transpressional left-lateral and oblique to reverse movements. Both these fault systems, displace all the stratigraphic succession up to the younger term, which correspond to the Palombini shale (Figs. 2A, 4A), constraining their age to post- Early Cretaceous, according to the eo-Alpine deformation.

The superposition of transtensional right-lateral movements on ENE- to NE-striking faults, which agree with a WNW-oriented regional shortening direction (Fig. 2B), document a further reactivation of previously existing faults. In the NCZ, these faults obliquely cut the mylonitic deformation (i.e., the Internal Canavese Line *sensu* Biino and Compagnoni, 1989) that juxtaposes the CZ and the Ivrea – Verbano Zone (Fig. 5L). This suggests that the present-day contact between these two zones corresponds to a younger brittle shear zone, likely reactivated during the tectonic exhumation of the Sesia Zone along the External Canavese Line (Fig. 5M). Although stratigraphic markers to temporal constraint this fault activity are lacking, it is well comparable with the Oligocene – Early Miocene tectonics which displaced Oligocene volcanics to the North of the studied sector (e.g., Berger et al., 2012; see also Lanza, 1984).

5. Structural setting of the mantle rocks in the Southern Canavese Zone

The structural setting of the SCZ is well comparable with the above described one, with the only difference that it is gradually rotated to N-S trend and, consequently, the main faults are here NNW- and NNE-striking (Figs. 6A, 6B and 6C). The interlacing of these two main fault systems define lenticular to elongated tectonic slices, which juxtapose the LMU, the post-Variscan intrusives, and different terms of the Paleozoic – Mesozoic succession to serpentinized mantle peridotites. The latters, represent a main elongated tectonic slice, dipping at high-angle toward ENE, which is tectonically bounded by orthogneiss, partly transformed into migmatitic gneiss and intruded by leucogranite, and by the volcanic member of the Collio Formation to the West and East, respectively, along high-angle NNW-striking right-lateral faults with anastomosed geometry. Toward North, the easternmost fault depicts an horse-tail geometry along which mantle rocks, volcanic rocks and yellowish to greenish pelites, alternating with rare red radiolarian-bearing chert levels (i.e., Selcifero Lombardo), are sliced and folded to locally define a narrow syncline with SSE-plunging fold axis. The contact between the Selcifero Lombardo and serpentinites is always tectonic (Fig. 3A) and locally a meters-thick horizon of grayish volcanic rocks, which was never documented before, is interposed (Figs. 6A-B). Importantly, far from the main faults, Middle Triassic massive dolostone originally cropped out, likely in primary stratigraphic contact between the Early Permian volcanics of the Collio Formation and the post-extensional Selcifero Lombardo (see Novarese, 1929; Baggio, 1965a). Although they are now lacking because of intense quarry activity, we have restored the primary position of dolostone in Fig. 6 according to literature data (Novarese, 1929; Baggio, 1965a). A NNW-trending cleavage (i.e., parallel to the main fault) also occurs and can be related with Alpine deformation. Cataclastic deformation related to this stage also affects volcanic rocks along the main faults. Regional-scale N-S trending strike-slip faults has been also detected SW of the SCZ, along the inner sector of the Alpine accretionary wedge (see Balestro et al., 2009, and Perrone et al., 2010)

6. Discussion

In this section we discuss in a regional tectonic framework the significance of our multidisciplinary and multiscale data from the CZ to redefine: (i) the nature and characteristics of the Variscan metamorphic basement, (ii) the role played by Late Carboniferous to Early Triassic structural inheritance in the break-up of the passive continental margin of Adria and Alpine Tethyan mantle exhumation, and (iii) the significance of the CZ in the geodynamic evolution of the Alpine Tethys.

6.1. Redefinition of the Variscan metamorphic basement and its nature

Our data show that the Variscan basement of the CZ consists of two superposed units (i.e., the LMU and UMU), which are characterized by different stratigraphy and are separated by a discontinuous horizon of mafic rocks. The tectonic coupling between these units is constrained to Variscan time by the common amphibolite-facies Variscan metamorphic foliation overprinting the two units in the CCZ.

In the UMU, the occurrence of preserved sedimentary textures in both the metasandstone and metasiltstone, suggests that these metasediments correspond to a monometamorphic complex and derive from a sedimentary and volcanic succession likely of Silurian – Devonian age. On the contrary, the pervasive deformation and the absence of preserved stratigraphic markers, would suggest that the metasediments of the LMU (i.e, the micaschist) correspond to a polymetamorphic complex. This would also be highlighted by the occurrence of bodies of orthogneiss within the micaschist, suggesting that pre-Variscan granitoid, likely of Ordovician age, intruded an already metamorphosed basement. The discontinuous occurrence of up to 10 m thick amphibolite, likely of basaltic origin, interposed between the LMU and the UMU, is well-comparable with the internal structure of the Southern Alpine metamorphic basement where it is inferred to mark a Variscan tectonic contact (i.e., The Strona Ceneri Border Zone; Giobbi-Origoni et al., 1982; Boriani et al., 1990). Thus, our findings suggest an affinity between the LMU and UMU and the Scisti dei Laghi polymetamorphic complex and Strona Ceneri monometamorphic complex of the Southern Alpine Domain (Serie dei Laghi *Auct.*), respectively. Both the complexes were intruded by granitoid of Ordovician age, and are tectonically separated by slices of mafic and ultramafic rocks (e.g., Giobbi-Origoni et al., 1982; Boriani et al., 1990). Similar interpretations were already proposed by Borghi et al. (1996) and Sacchi et al. (2007) for the NCZ and CCZ.

Plutonic rocks correspond to a magmatic suite consisting of minor gabbro, diorite and tonalite, and of widespread granite, which intruded rocks both of the LMU and UMU. The occurrence of hypoabissal dykes within granitoid bodies highlights the existence, within the same magmatic event, of a first intrusive stage followed by a mixed intrusive and volcanic one. These dykes also occur in the LMU and UMU, proving that the whole Variscan basement was located at a shallow crustal level at time of intrusion.

This overall magmatic activity can be referred to that one of the Sesia Magmatic System, which affected the upper crust of the Serie dei Laghi (i.e., “Graniti dei Laghi” *Auct.*) and the lower crust of the Ivrea - Verbano Zone (i.e., “Mafic Complex” *Auct.*) in Early Permian age (Quick et al., 2009 and reference therein; see also Pin, 1986; Mayer et al., 2000), with different pulses of mafic to acidic plutonic activity and volcanism within 10 Ma intervals (about 290 and 280 Ma), and with ascent and emplacement of magmas facilited by trastentional faulting (Rottura et al., 1998; Handy and Steit, 1999; Handy et al., 1999).

Partial melting of the orthogneiss of the LMU is highlighted by its partial transformation into migmatite and by occurrence of pods, dykes and irregular masses of white mica-bearing leucogranite, which also emplaced within already cooled gabbro and diorite, and filled coeval NE-striking faults and fracture systems. The spatial association of the gabbro and diorite bodies with this anatectic leucogranite, would highlight that they represent the heating source for the partial melting process. The existence of a general heating event is also constrained by static growth of MT-HT minerals (i.e., biotite, white mica and garnet) in the micaschist of LMU. Since single clasts of the Verrucano deposits show evidences of this heating event, the latter could be regarded as of pre-Upper Permian age. As a matter of fact, a biotite from migmatitic gneiss of the CCZ has been dated as Middle Permian (264.0±3.9 Ma; Beltrando et al., 2014). This post-Variscan heating can be overall related to the so-called Permian HT metamorphic event (Schuster and Stuwe, 2008; Spalla et al., 2014), well-documented in the Southern Alpine Domain. Although this event is mainly recoded and documented in the Ivrea-Verbano lower crust, it also matched with “appinite” mafic to intermediate intrusions, which emplaced along the Cossato-Mergozzo-Brissago Line (i.e., the shear zone separating the Ivrea-Verbano zone from the Serie dei Laghi *Auct*; Garde et al., 2015, and reference therein) and locally induced partial melting (Mulch et al., 2002). The amphibole-bearing gabbro and diorite in the CZ are very similar to the appinite and, remarkably, they are spatially associated to the migmatitic gneiss in the study area.

As discussed in the following, the overall relationships between the architecture of the Variscan basement, emplacement of the post-Variscan intrusives and heating event in the CZ, have to be seen in the more general context of the strike-slip tectonics and crustal thinning which controlled magmatic activity and affected the Adriatic crust during the Permian period along the “Proto-Canavese Shear Zone” (see below).

6.2. Role of structural inheritance in the break-up of the passive continental margin of Adria and Jurassic mantle exhumation

After the Variscan orogeny, different pulses of a Late Carboniferous to Early Triassic strike-slip tectonics, which are documented for the first time in the CZ, are well-constrained through the crosscutting relationships between stratigraphic unconformities and mapped faults. In fact, the evidence that the Collio Formation is directly overlain onto both the LMU and UMU (Figs. 2A and 4), which are in turn juxtaposed along ENE- to NE-striking faults, suggests that this fault activity likely started since Late Carboniferous as also documented by the larger amount of displacement accommodated in the basement with respect to that observed within the Lower Permian succession (Fig. 4). In addition, above the Hercynian unconformity, the different thickness of the volcanic member of the Collio Formation, clearly documents deposition on structural highs and lows, bounded by ENE- to NE-striking (present day coordinates) transtensional faults (Figs. 4 and 7A), as well-documented in the Southern Alps during Early Permian – Early Triassic (see, e.g., Handy and Zingg, 1991; Cadel et al., 1996; Handy et al., 1999; Spalla et al., 2014; Marotta et al., 2018 and reference therein). This faulting activity continued with alternating intensity up to the unconformable overlain of the fluvial deposits in Verrucano facies (Late Permian), as well stated by the first partial sealing of the faults by lacustrine deposits of the upper part of the Collio Formation, and by the different thickness of Verrucano deposits (Figs. 4C and 4E). The occurrence in the Verrucano of clasts sourced from both the units of the Variscan metamorphic basement, volcanic rocks and intrusives, highlights that these different basement units were already exhumed in Late Permian. This is also supported by the direct overlain of Middle Triassic dolostone onto the different Paleozoic rocks and the Verrucano (Figs. 2A and 7A). Similar observations are also documented NE of the studied sector in the Southern Alps (see, e.g., Handy and Zingg, 1991; Handy et al., 1999 and reference therein). Here ENE-trending transtensional left-lateral faults (i.e., the Cossato – Mergozzo – Brissago Line) controlled both the deposition of the Collio Formation in narrow and elongated basins, and the exhumation of the lower crust in the Ivrea – Verbano Zone. Particularly, Handy et al. (1999) suggested, on the basis of petrological data, that different thermal pulses occurred after Carboniferous time, playing a significant role in affecting the pre-Alpine crust, potentially related with (and also following) the asthenospheric upwelling driven by the Late Triassic – Early Jurassic hyper-extension of the Adria margin (see also Smye and Stockli, 2014).

The above described articulated tectono-stratigraphic setting, above which the Triassic platform succession deposited, thus represents the structural inheritance at the onset of the Early Jurassic continental break-up of the passive margin of Adria (Fig. 7A). The gradual and abrupt change of facies and thickness of syn-extensional sediments (i.e., Muriaglio Formation) parallel (i.e., SW-NE direction) and across (i.e., NW-SE direction) of long-lived inherited faults, ENE- to NE-striking, document their syn-depositional reactivation in Early Jurasssic, likely as transtensional faults. The evidence that they bound SW-dipping high-angle extensional faults and, only in one case (in the Bric Figlia sector of the CCZ), a low-to medium-angle, NNE-dipping, extensional sheared Verrucano horizon, tens of meters long and up to few meters thick, suggest that the reactivation of ENE- to NE-striking faults controlled the deposition of Lower Jurassic syn-extensional sediments into elongated transtensional pull-apart basins (Fig. 7B).

The occurrence of different clastic to brecciated deposits at the base of the syn-extensional deposits, showing different monomictic (i.e., mainly dolostone) and polymictic (i.e., from the Variscan metamorphic basement to dolostone) composition of clasts, and their uncoformable deposition onto different terms of the pre-Jurassic succession (i.e., from the Variscan metamorphic basement to the Middle Triassic platform dolostone), agree with vertical fault displacements not compensated by sedimentation and different facies deposited on the different sides of structural highs (e.g., along the fault scarp and the tilted hangingwall; see Bernoulli et al., 1990; Bertotti, 1991). In fact, it is evident that the offset of these Early Jurassic faults is commonly limited to only few tens of meters as constrained by the maximum thickness of the syn-extensional succession (Figs. 4), also supporting that the exhumation of different terms of the pre-Mesozoic succession was in large part inherited by Late Carboniferous - Early Triassic tectonics.

If we consider that a large amount of extensional displacement and crustal thinning is documented to occurred during pre-Jurassic trastensional wrenching, our data suggest that extension along low-angle detachment faults was not the only and most efficient mechanism in stretching and thinning the CZ continental crust. This is also suggested by the lack of any Jurassic-related low-angle extensional faults (i.e., corrugated surfaces) and associated cataclastic to mylonitic deformation within the metamorphic basement and volcanic rocks, as commonly expected and observed in both continental (e.g., Sholz, 1987; Bernoulli et al., 1990; Manatschal, 2004; Shipton et al., 2006; Handy et al., 2007; Froitzheim et al., 2008) and oceanic (e.g., John, 1987; Cann et al., 1997; Cannat, 1993; Balestro et al., 2015, 2018; Festa et al., 2015a; Frassi et al., 2017) settings, independently on the time of deformation. On the contrary, a lithospheric wrenching controlled by a new step of strike-slip faulting associated to an oblique rifting under a roughly E-W regional-scale extension, which reactivates pre-existing Paleozoic faults and rheological weakness and discontinuities, seems to better agree with the documented tectono-stratigraphic setting here redefined for the CZ. As in the Southern Alps, the pre-Jurassic (i.e., Variscan to Permian – Early Triassic) extension is, in fact, required to obtain the observed crustal extension, thinning and mantle exhumation (see, e.g., Handy et al., 1999; Spalla et al., 2014; Marotta et al., 2018 and reference therein). Limited vertical displacement of syn-extensional Jurassic faults, clearly shows that the contribute of emergent Jurassic faults and local low-to medium angle detachment ones, was ineffective in producing and justifying the important crustal thinning inferred for the CZ evolution as distal passive margin of Adria.

Although out of the aim of this work, we suggest that inferred detachment faults able to stretch the CZ continental crust, up to mantle exhumation, could be concentrated at deeper structural levels, which are not exposed in the studied sector. In continental crust, they are commonly expected to be characterized by significant deformation, ranging from gouge, cataclasites, and mylonities (e.g., Caine et al., 1996; Florineth and Froitzheim, 1994) in several tens of meters-thick horizons (e.g., Handy et al., 2007; John and Cheadle, 2010; Whitney et al., 2012). On the contrary, if those detachment faults cut serpentinized mantle rocks, they may evolve differently, as serpentinite can create weaker faults, longer duration activity, and relatively low thickening gradient of fault zones (e.g., Nur Shuba et al., 2018 and reference therein). Although in the SCZ, potential primary relationships between the serpentinized peridotite and both Lower Permian volcanic rocks and Middle-Upper Jurassic post-extensional sediments are not excluded to existed documenting mantle exhumation, the occurrence of remnants of emergent detachment fault cutting serpentinite is now masked and/or overprinted by Alpine tectonics.

6.3. Significance of the Canavese Zone in the geodynamic evolution of the Alpine Tethys and Western Alps

The documented different pulses of Late Carbonifeous – Early Triassic strike-slip tectonics, which wrenched the already deformed Variscan metamorphic basement and controlled the Paleozoic deposition, is consistent with the long-lasting regional-scale wrench tectonics (Fig. 8A; i.e., the "East-Variscan Shear Zone" *Auct.*), associated with the transition from Pangea B to Pangea A (*sensu* Muttoni et al., 2003) and the opening of the western Neo-Tethys during Early- to Late Permian time (Fig. 8A). This global-scale event, which reactivated the Variscan orogenic trends (e.g., Matte, 1986; Massari, 1988), is inferred to have connected deep mechanical instabilities in the mantle with low crustal magmatism, and with wrenching of the upper crust across periodically active tectonic pathways (e.g., Handy et al., 1999; Muttoni et al., 2003; Spalla et al., 2014 and reference therein). The evidence and characteristics of Early Permian to Early Triassic strike-slip tectonics documented for the CZ may thus correspond to one of these regional-scale active tectonic pathways, which characterized large part of the Variscan belt North of the Adria microcontinent (Fig. 8A). Transtensional left-lateral kinematics documented in the studied sector, along the ENE- to NE-striking faults, on the basis of geological mapping data (see also Robustelli et al., 2018 for additional paleomagnetic constraints), well agree with those described by Handy et al. (1999) to the NE for the Cossato – Mergozzo – Brissago Line, and interpreted as a conjugate fault of the East-Variscan Shear Zone *Auct*. Alternatively, it is not excluded and possible to discriminate in the studied sector, that the documented right- and left-lateral kinematics were, on the contrary, related to the switch of regional shortening from NW-SE to NE-SW directions as in the Southern Mediterranean Region (e.g., Houari and Hoepffner, 2003; Simancas et al., 2009; Michard et al., 2010).

The close relationships between the Permian heating event and emplacement of post-Variscan intrusives in the CZ, as well as in the whole Southern Alpine Domain, document the product of the connection between crustal wrenching, related to strike-slip tectonics, and magmatic activity, which in turn produced thermal perturbations leading to partial melting. During Early Permian, in fact, the Adriatic lower crust was intruded by gabbros from the Northern Apennines (e.g., Montanini and Tribuzio, 2001) to the Austroalpine (e.g., Bussy et al., 2001; Ballèvre et al., 2018), and Southern Alpine (e.g., Pin, 1986; Mayer et al., 2000) domains, facilitated by deep-reaching transtentional faults (e.g., Rottura et al., 1998; Handy et al., 1999). Similar evolution developed in connection with an "hot" strike-slip tectonics and volcanism, also occurred in Central Europe (e.g., Muttoni et al., 2003 and reference therein).

As it is largely documented that the onset of the Permian lithospheric wrenching, which drove the Permian Pangea transformation, was favored by the Variscan orogenic inheritance (e.g., weakened state of the crust, reactivation of Variscan sutures, etc., see, e.g., von Raumer et al., 2013; Spalla et al., 2014; Marotta et al., 2018 for a complete review), our findings document that the onset of the continental break-up and Jurassic rifting of the Alpine Tethys was strongly controlled by Paleozoic structural inheritances also in the CZ (Fig. 8). Similar pre-existing high-strain zones or suture zones were, in fact, documented controlling continental break-up and rifting stages in different continental margins throughout the world (see, e.g., Frimmel and Hartnady, 1992; Basei et al., 2008; Buiter and Torsvisk, 2014; Petersen and Shiffer, 2016; Will and Frimmel, 2018 for a complete review).

Alternative studies document that hyper-extension with crustal allochthonous separated by exhumed mantle, often observed in magma-poor margins, can be explained by extension of continental crust with pre-rift serpentinite preserved below (e.g., fossil mantle wedge; see Peterson and Shiffer, 2016). Marotta et al. (2018) document, in fact, that if the Adria rifting developed in a stable lithosphere, Triassic – Jurassic HT-LP metamorphism is predicted together with gabbro-basalt production younger than 185 Ma instead of the observed Permian – Early Triassic metamorphic and igneous record. Indeed, this has never been detected in the Alpine continental crust, thus mantle serpentinization occurred before crustal-break up and the denudation occurred before ocean spreading (Marotta et al., 2018), and the opening of the Alpine Tethys did not start in a stable continental lithosphere but developed by recycling part of the old Variscan collisional suture (Figs. 8B and 8C).

The occurrence of serpentinized peridotite in the SCZ is also strongly complicated by Alpine tectonics (see Fig. 6). In fact, although mantle exhumation occurred in the Jurassic in the Alpine Tethys, the primary architecture and size of the original ocean-continent transition zone (OCT) from the Adria passive margin to the exhumed "continental mantle" (*sensu* Dilek and Furnes, 2011) cannot be simply restored in the CZ because of Alpine-related deformation. It is important to note, in fact, that the association of mantle and continental crustal rocks in the Rocca Canavese Complex of the Sesia Zone (Figs. 2A and 9), which is tectonically juxtaposed to the SCZ through the External Canavese Line, has been recently interpreted as the product of an Alpine-related tectonic mélange (Roda et al., 2018). Similarly, the northeastern continuation of the CZ in the Biella sector has been defined "Canavese tectonic mélange" by Berger et al. (2012), emphasizing once again the significant mixing role of the Alpine tectonics.

Although out of the aim of this work, since Late Cretaceous the Alpine reactivation and inversion of the long-lived Late Carboniferous to Jurassic inherited faults occurred, up to the present day structural setting with the CZ sliced between the Sesia Zone and the Ivrea - Verbano Zone along the External and Internal Canavese Lines, respectively. Therefore, our findings suggest that the ENE- to NE-trending of part of the faults of the CZ, roughly represent an ancient (since Late Carboniferous - Early Permian) and polyphasic major discontinuity and/or shear zone (i.e, the Proto-Canavese Shear Zone), which controlled the evolution of the continental margin of Adria from the onset of the East-Variscan Shear Zone (Figs. 8A) to the Jurassic rifting (Figs. 8B-D) and subsequent Alpine collisional stages and exhumation (Fig. 9). Since the onset of the Jurassic rifting, the Proto-Canavese Shear Zone likely controlled the segmentation of the continental margin of Adria (compare Figs. 8B and 8C), separating the present day Sesia Zone from the Southern Alps (Fig. 8D) through the formation of a narrow and elongated basin, gradually widening toward SW (present-day coordinates), along which mantle spread out in forming the present day Lanzo Ultramafic Complex (Piccardo, 2010) as a branch of the Alpine Tethys.

During the collisional Alpine stage, the Canavese Shear Zone likely acted as a backstop of the accretionary complex (Fig. 9), separating the E- to SE-dipping Alpine subduction zone from the Southern Alpine retrowedge. At this stage, it roughly corresponded to the Proto-Insubric Line whose pre-collisional activity is also documented, according to our findings, to the NE in the Orobic Southern Alps (see Zanchetta et al., 2015).

7. Concluding remarks

Detailed geological mapping (1:5,000 scale) and stratigraphic and structural analyses, allowed to define a new tectono-stratigraphic setting of the Variscan metamorphic basement and Paleozoic-Cenozoic stratigraphic succession, and the tectonic evolution from the late Variscan stage to Alpine ones in the framework of the continental break up of Pangea and exhumation of the Alpine Tethyan mantle. Particularly, our finding document that the CZ corresponds to a narrow inherited, and long-lived polyphasic strike-slip deformation zone (i.e., the Proto-Canavese shear zone), which played a significant role in controlling the multistage tectonic evolution of this sector of the present-day Western Alps from the late Variscan stage to the Alpine convergent stages and following exhumation, passing through the Pangea continental break-up and the following Jurassic exhumation of the Alpine Tethyan mantle. Thus, it is significant to outline that in the CZ the Jurassic tectonic dismemberment of the distal passive margin of Adria, up to mantle rocks exhumation, did not simply result from syn-rift Jurassic extension but was strongly favored by an older structural inheritance (the Proto-Canavese Shear Zone), which controlled earlier lithospheric weakness, as also suggested for other sectors of the Southern Alpine domain (e.g., Cadel et al., 1996; Spalla et al., 2014; Marotta et al., 2018) for which the CZ represents the southwestern prolongation. Our finding document a close affinity between: (i) the LMU and UMU of the Variscan basement of the CZ and the Scisti dei Laghi polymetamorphic Complex and the Strona Ceneri monometamorphic Complex of the Southern Alpine Domain (Serie dei Laghi *Auct.*), respectively, and (ii) the Upper Carboniferous to Lower Cretaceous succession of the Lombardian Basin in the Southern Alps.

In conclusion, our results demonstrate that in orogenic belts, characterized by structural and metamorphic complexities and polyphasic deformation as in the Western Alps, the recognizing and understanding of the role played by pre-Jurassic structural inheritances represent key factors that are essential for reconstructing not only the tectonic history from the continental break up of Pangea to the onset of the Alpine Tethyan oceanic basin, but the whole tectonic evolution of the orogenic belt. The large amount of extensional displacement and crustal thinning occurred during different pulses of Late Carboniferous – Early Triassic strike-slip tectonics is well-consistent with the role played by long-lived regional-scale wrench faults (e.g., the East-Variscan Shear Zone). This should be strongly taken in consideration in models aimed to understand processes and mechanisms of progressive stretching and lithospheric thinning, driving to the sharp decrease in crustal thickness and strong decoupling between upper crust and continental mantle, up to continental breakup and mantle exhumation of the Jurassic Alpine Tethys (i.e., the Ligurian – Piedmont Ocean). Thus, in complex orogenic belts, it is essential, and cannot be renounced to constrain multidisciplinary analytical studies (e.g. structural, stratigraphic, petrological) on new detailed geological maps (see also Şengör, 2014), and on the description of crosscutting relationships between stratigraphic uncoformities and mapped faults, if we aim to really understand their tectonometamorphic evolution, and better constrain palaeogeographic reconstructions.

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Figure captions

Figure 1 – (A) Structural sketch of the Alps-Apennine orogenic system (modified from Festa et al., 2015b) and location of the map shown in Figure 1B. (**B**) Tectonic map of the Northwestern Alps and the Northern Apennines (modified from Balestro et al., 2015) with the location of the studied sector (red line).

Figure 2 – (A) Structural sketch of the Canavese Zone (CZ), displaying the tectonic relationships with the Ivrea-Verbano Zone and Sesia Zone, and related stratigraphic columnar sections (not to scale), showing the tectono-stratigraphic relationships between the different lithological units in the Southern (SCZ), Central (CCZ) and Northern (NCZ) sectors of the CZ (thickness of the lithostratigraphic units are in the text). *Mantle rocks*: Serpentinite (SRP); *Variscan basement*: Lower Metamorphic Unit (LMU), Amphibolite (AMP), Upper Metamorphic Unit (UMU); *Early to Middle Permian post-Variscan intrusives*: Gabbro and Diorite (GBD), Granite and Tonalite (GRT), Hypoabissal dykes (HBD), Leucogranite (LGR); *Upper Carboniferous to Middle Triassic pre-extensional succession*: Basal Conglomerate (CGB; Late Carboniferous - Early Permian); Volcanics (COL1), Volcanoclastics (COL1a) and lacustrine deposits (COL2) of the Collio Formation (Early Permian); Verrucano (VER, Late Permian); Dolostone (DOL, Middle Triassic); *Lower - Middle Jurassic syn-extensional succession*: Clastic member (MUF1), Arenaceous member (MUF2), Siltitic-Arenaceous member (MUF3), and Limestone member (MUF4) of the Muriaglio Formation (Early – Middle Jurassic); *Upper Jurassic - Lower Cretaceous post-extensional succession*: Shaly member (SEL1) and Siliceous member (SEL2) of the Selcifero Lombardo (Middle - Late Jurassic); Calpionella Limestone (CAL, Tithonian - Berriasian); Palombini Limestone (APA, Early Cretaceous). (**B**) Representative mesoscale data (Schmidt net, lower hemisphere) of main Alpine-related strike-slip faults bounding and crosscutting the CZ succession: (1) transpressional left-lateral faults, and (2) superposed transtensional right-lateral ones; (n.: number of fault planes; black arrows represent slikenslines; blue, green and red squares show the maximum, intermediate and minimum shortening axes, respectively).

Figure 3 – Images of the Variscan metamorphic units and Paleozoic lithostratigraphic units and structures at different scales: (**A**) Close-up photo of the tectonic contact (dashed red line) between Serpentinite (SRP) and the Selcifero Lombardo (SEL1) to the NW of Mt. Piedmonte in the SCZ; (**B**) Close-up of the intrusive relationships (blue line) between diorite (GBD) and the migmatitized orthogneiss of the Lower Metamorphic Unit (LMU) in the CCZ (T. Piova area), both injected (black lines) by the leucogranite (LGR). Note that the set of fractures, which is parallel to the fault (dashed red line) is filled by leucogranite injection. Dashed black lines indicate the Variscan foliation; (**C**) Close-up view of the intrusive contact (dashed white lines) of the granophyre hypoabissal dyke (HBD) with the orthogneiss of the Lower Metamorphic Unit (LMU), close to Vidracco village in the CCZ. Dashed black lines indicate the Variscan foliation. Hammer for scale; (**D**) Close-up of the amphibolite characterizing the mafic horizon, which separates the LMU and UMU of the Variscan metamorphic basement in the CCZ (SSE of Bric Figlia); (**E**) Well-bedded (dashed white line) alternating medium-grained metasandstone and fine-grained metasiltstone of the Upper Metamorphic Unit in the CCZ (South of Bric Figlia), deformed by Late-Variscan open folds. Hammer for scale; (**F**) Close-up view of the diorite (GBD) intruded (dashed white line) by a granite dyke (GRT) in the NCZ (ESE of Borgofranco d'Ivrea); (**G**) Close-up photograph of the continental fluvial deposits of the Basal Conglomerate (Late Carboniferous), showing rounded to irregular clasts, consisting of fragments of quartz veins, metasandstone, micascist, and gneiss, embedded in coarse-grained arenite of the same composition of clasts (CCZ, close to Serra Alta); (**H**) Close-up view of the angular unconformity (dotted blue line) superposing the Verrucano (VER; Late Permian) onto both the metasediments of the UMU and the Volcanic Member of the Collio Formation (COL1, Late Permian) to the South of Bric Figlia in the CCZ (dashed white line represents the attitude of bedding). The yellow dotted line represents the unconformity at the base of the Collio Formation. Hammer for scale; (**I**) Polished sample of the sheared Verrucano horizon, showing the strong elongation of clasts according to a roughly ENE-oriented extensional stretching direction (ENE of Bric Figlia in the CCZ).

Figure 4 – Simplified geological map (**A**) of the Central Canavese Zone (Bric Figlia area) and related geological cross-sections (**B** and **C**), showing the tectono-stratigraphic relationships between the different terms of the Variscan metamorphic basement and the overlying Paleozoic- to Mesozoic stratigraphic succession. Restored cross sections (**D** and **E**) at the Middle – Late Jurassic time show the tectonic control of pre-Jurassic inherited faults in the deposition of the Permian succession (Collio Formation and Verrucano), as documented by the abrupt change of thickness of these lithostratigraphic units in sectors bounded by faults (see text for details). The "null point" indicates the change from extension/transtension to net contraction/transpression. Acronyms of the lithostratigraphic units as in Figure 2.

Figure 5 – Images of the Mesozoic lithostratigraphic units and structures at different scales: (**A**) Panoramic view of the stratigraphic contact (dotted blue line) between the Middle Triassic platform Dolostone (DOL) and the syn-extensional succession of the Muriaglio Formation (MUF) in Montalto Dora, NCZ; (**B-D**) Close-up view of different facies of the Clastic Member of the Muriaglio Formation through the CZ. In the CCZ (E of Bric Figlia) it shows (**B**) clast-to matrix-supported polymicitic angular to sub-angular clasts (orthogneiss, amphibolite and metasandstone of the Variscan metamorphic basement, volcanic, granitoid, and rare dolostone fragments), embedded in a coarse-grained yellowish to reddish matrix (pencil for scale). In the SCZ (N of Levone) (**C**) it differs on a major content of Triassic dolomitic clasts, which are mostly lacking (**D**) in the NCZ (Montalto Dora); (**E**) Close-up of the Arenaceous Member of the Muriaglio Formation, showing medium-to coarse grained sandstone, passing upward to dark-reddish fine-to medium grained sandstone and siltstone (Muriaglio in the CCZ); (**F**) Close-up view of the Siltitic-arenaceous Member of the Muriaglio Formation, showing dark gray pelitic to fine-grained sandstone levels, alternating to grayish sandstone, in cm-thick horizons (Montalto Dora in the NCZ); (**G**) Close-up photograph of the Limestone Member of the Muriaglio Formation, consisting of alternating limestone and sandstone in decimeters thick beds (Montalto Dora in the NCZ); (**H**) Close-up view of the reddish argillite, alternating with yellowish-greenish pelite of the Selcifero Lombardo close to Muriaglio in the CCZ; (**I**) Outcrop view of alternating reddish to pinkish

radiolarian-bearing cherts and shale (i.e., Radiolarites *Auct.*) of the Selcifero Lombardo (E of Campo C.se in the CCZ); (**L**) Outcrop view of the Internal Canavese Line (ICL; red line) at Montalto Dora in the NCZ, which tectonically juxtaposes the gabbro of the Ivrea-Verbano Zone (IVZ) to the Limestone Member of the Muriaglio Formation of the Canavese Zone succession (CZ). This mylonitic contact is displaced by brittle faults (black lines). Dashed white lines indicate the mylonitic foliation; (**M**) Panoramic view of a transtensional flower structure (dashed red lines) within the shear zone of the External Canavese Zone, which juxtaposes the Sesia Zone with the Muriaglio Formation of the Canavese Zone (E of Borgofranco d'Ivrea in the NCZ); (**N**) Close-up view of a transtensional strike-slip duplex developed in the uppermost part of the metasandstone of the Upper Metamorphic Unit (UMU) of the Variscan basement (Bric Filia in the CCZ). This type of structures commonly displace the overlying Collio Formation and Verrucano with the same geometry. Hammer for scale.

Figure 6 – Simplified geological map (**A**) of the Southern Canavese Zone (Levone area) and related geological cross-sections (**B** and **C**). Note that the primary position of Triassic dolostone, which is now totally lacking in outcrop because of the intense quarry activity, has been restored on the basis of literature data (Novarese, 1929; Baggio, 1965a).

Figure 7 – (**A**) Schematic cross-section showing the tectono-stratigraphic relationships between pre-Middle Triassic inherited faults and sediment deposition in the CZ. Note the tectonic control of faults in the deposition of the Permian succession (Collio Formation and Verrucano). Acronyms of the lithostratigraphic units as in Figure 2. (**B**) Simplified sketch (map view, not to scale), showing the relationships between reactivated inherited strike-slip faults, ENE- to NE-striking (red lines), and newly formed extensional faults, NW-striking (black line), at the onset of the Early Jurassic extension. The interlacing between these high-angle faults, and possibly local low-angle detachment faults (dotted blue line), controlled the deposition of the Lower Jurassic syn-extensional sediments of the Muriaglio Formation into elongated transtensional pull-apart basins. Thick red arrows indicated the regional direction of extension.

Figure 8 –Paleogeographic reconstructions (in map) of: (**A**) the Variscan Belt at Early Permian, showing its complex structural zonation related to wrench tectonics along main dextral strike-slip fault zones (e.g., the East-Variscan Shear Zone) and associated left-lateral ones (modified from Ballèvre et al., 2018, and from Stampfli et al., 2002; Schettino and Turco, 2011); (**B**) the onset of the continental break-up at Late Triassic (modified from Stampfli et al., 2002; Schettino and Turco, 2011), showing its close relation with the strike-slip faults inherited from the Early Permian wrench tectonics (dashed red lines); (**C**) the location of the active rifting of the future Alpine Tethys and continental crust thinning at Early Jurassic (modified from Stampfli et al., 2002; Schettino and Turco, 2011). In all figures, the location of the Canavese Zone (blu star) is inferred from Stampfli et al. (2002) and Schettino and Turco (2011). (**D**) Schematic regional cross-section through the Alpine Tethys at Late Jurassic – Early Cretaceous (modified from Manzotti et al., 2014), showing the location of the "Proto-Canavese Shear Zone" at the distal passive margin of the Adria microplate.

Figure 9 – (**A**) Paleogeographic reconstructions (in map) of the Alpine Tethyan realm in the Late Cretaceous (modified from Stampfli et al., 2002; Schettino and Turco, 2011; Festa et al., 2013), showing the location of the Canavese Zone, and its potential role as a backstop of the Alpine accretionary complex, separating the E- to SE-dipping Alpine subduction zone from the Southern Alpine retrowedge, during Late Cretaceous (**B**) and Late Eocene (**C**) convergent stages (modified from Manzotti et al., 2014). (**D**) Simplified cross-section, showing the Late Oligocene – Early Miocene right-lateral reactivation of the Canavese Shear Zone during the exhumation of the Sesia Zone (modified from Manzotti et al., 2014).

Figure 1

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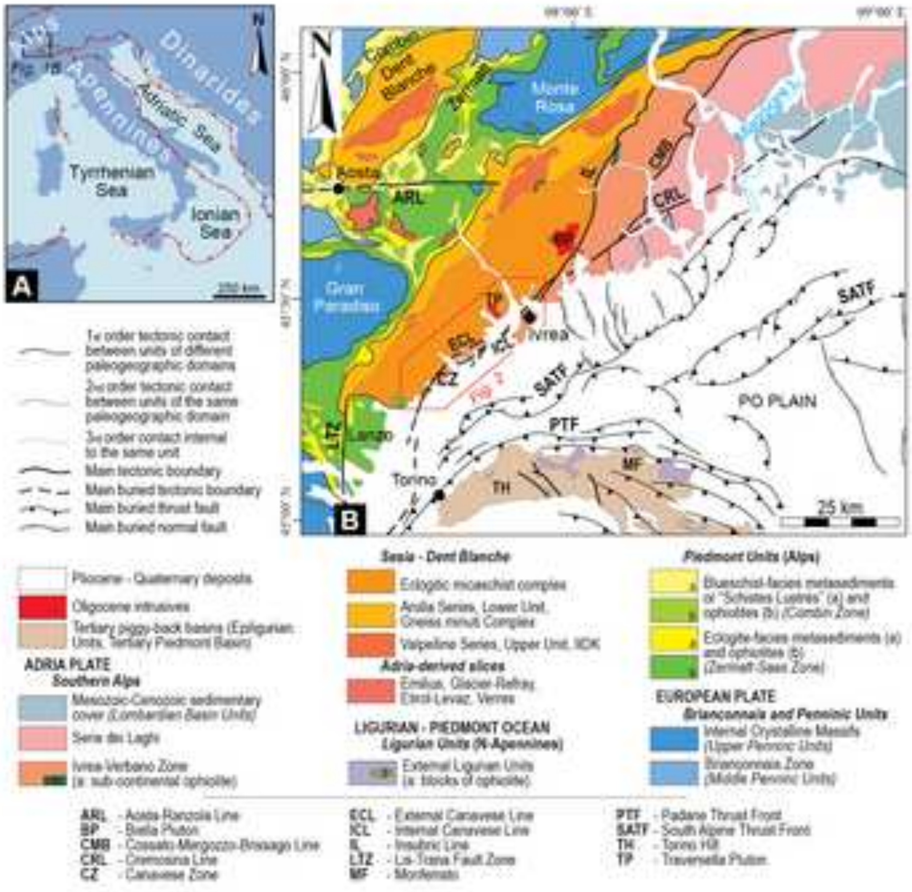

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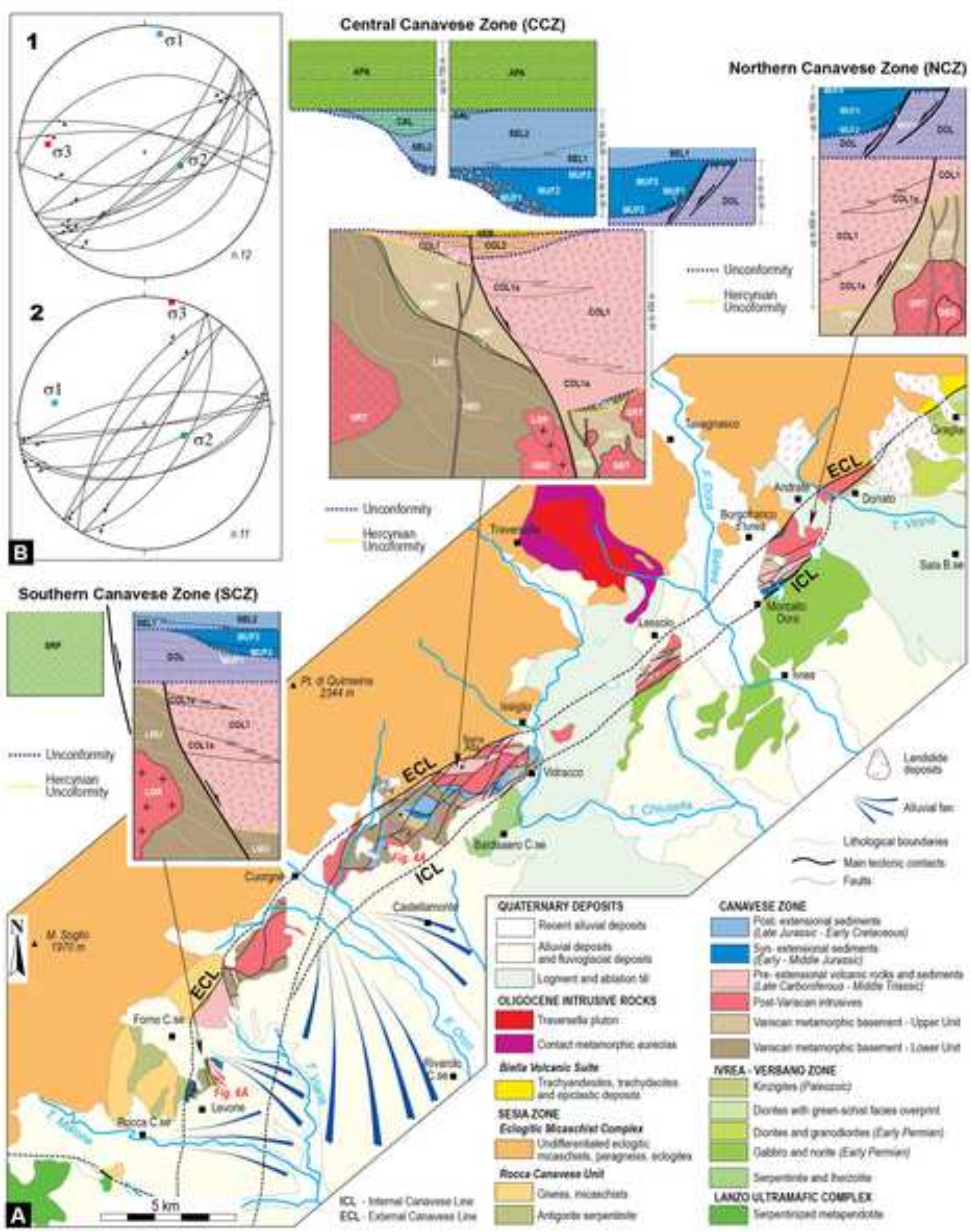

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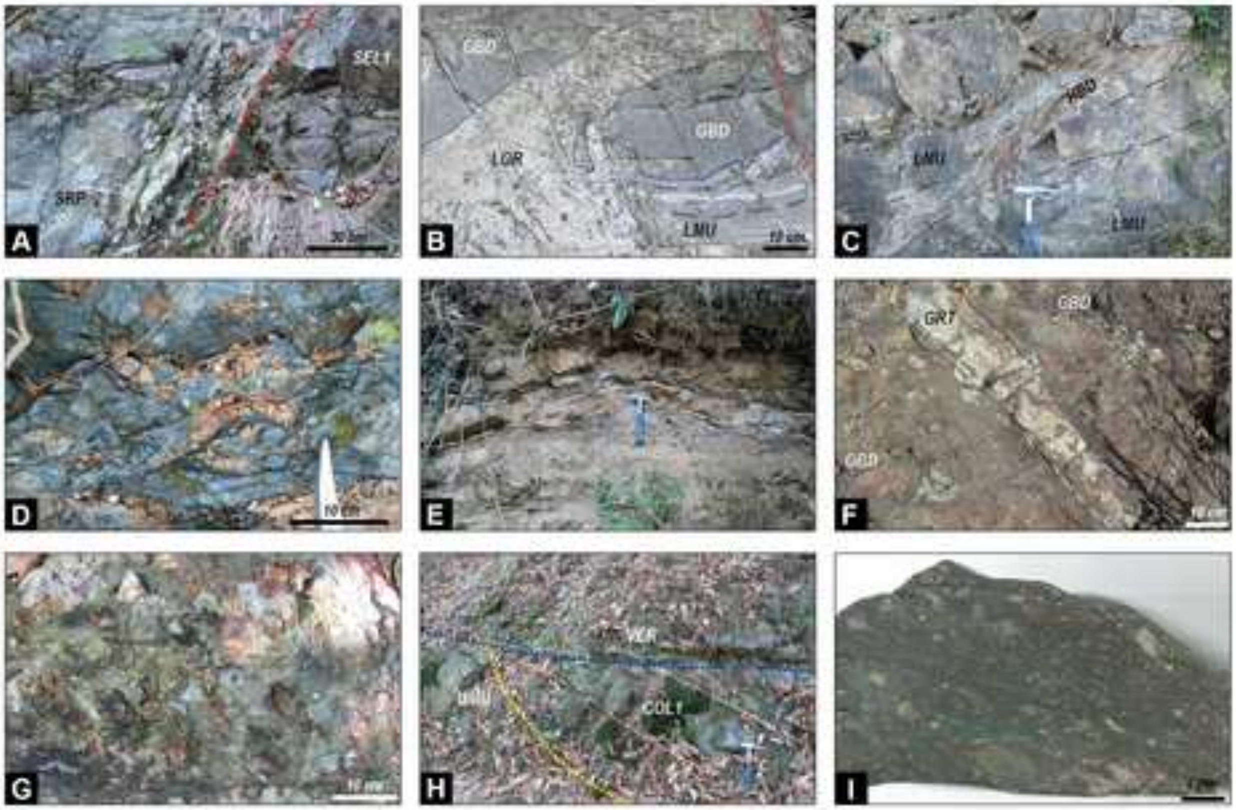

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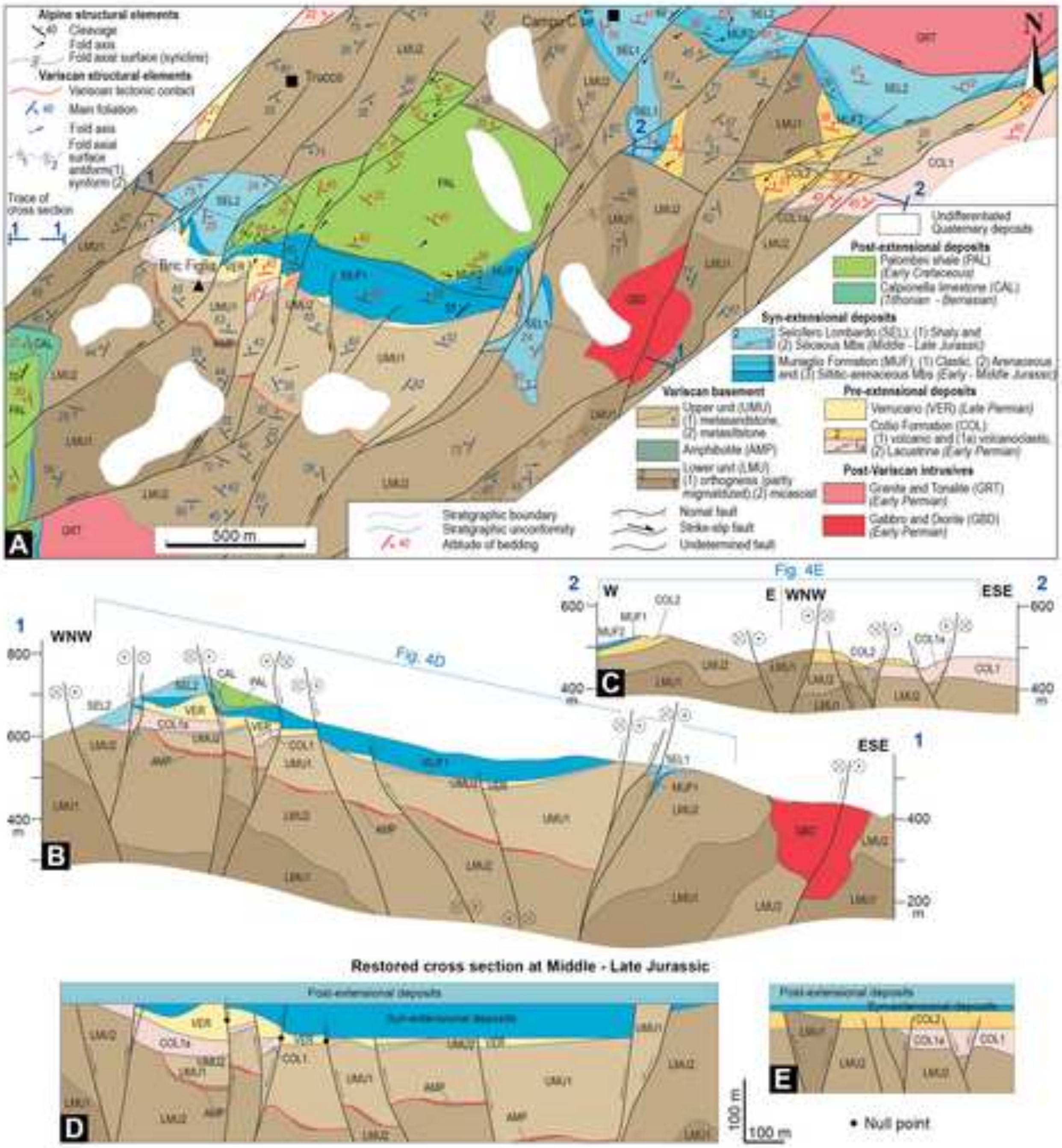

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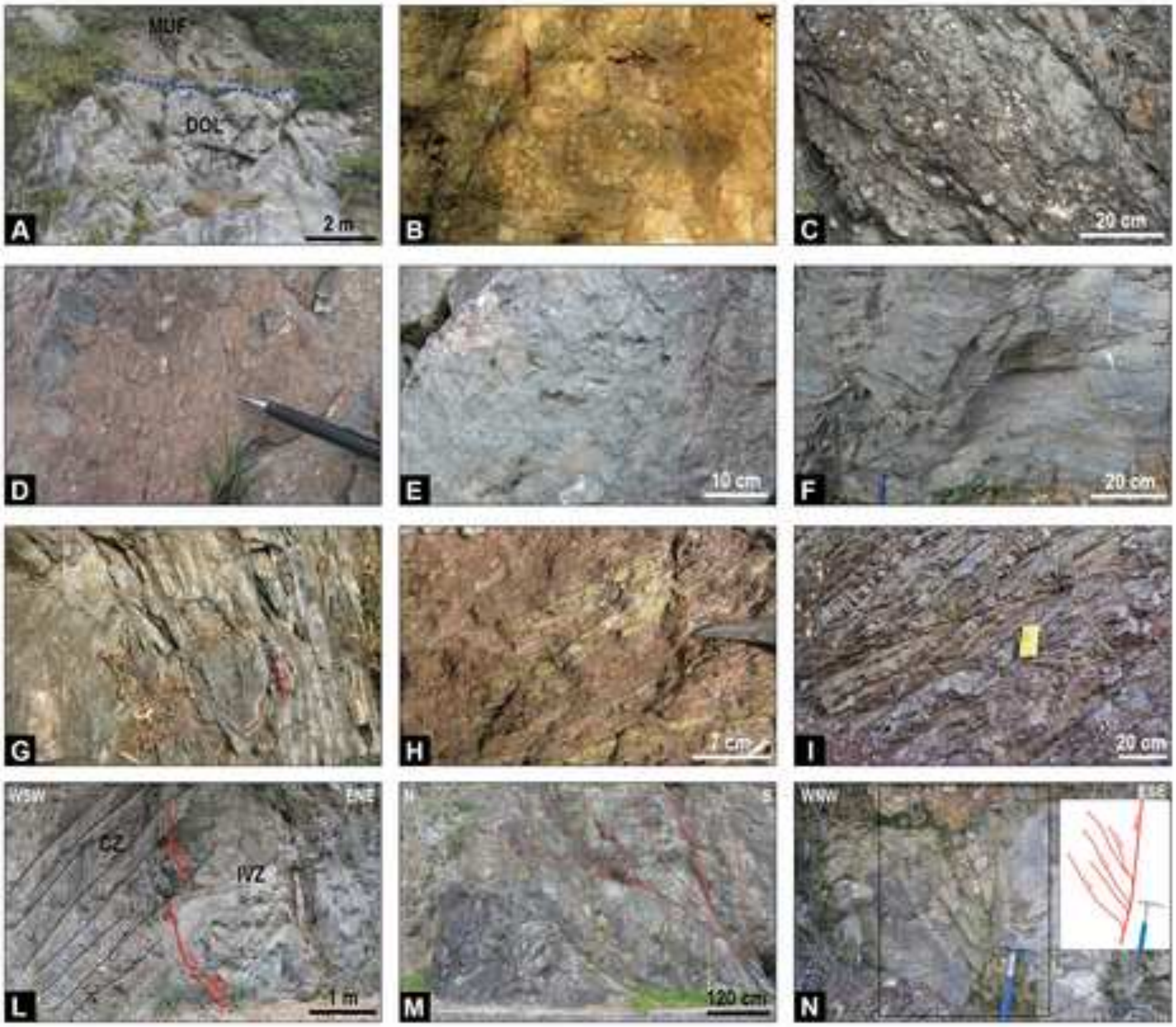

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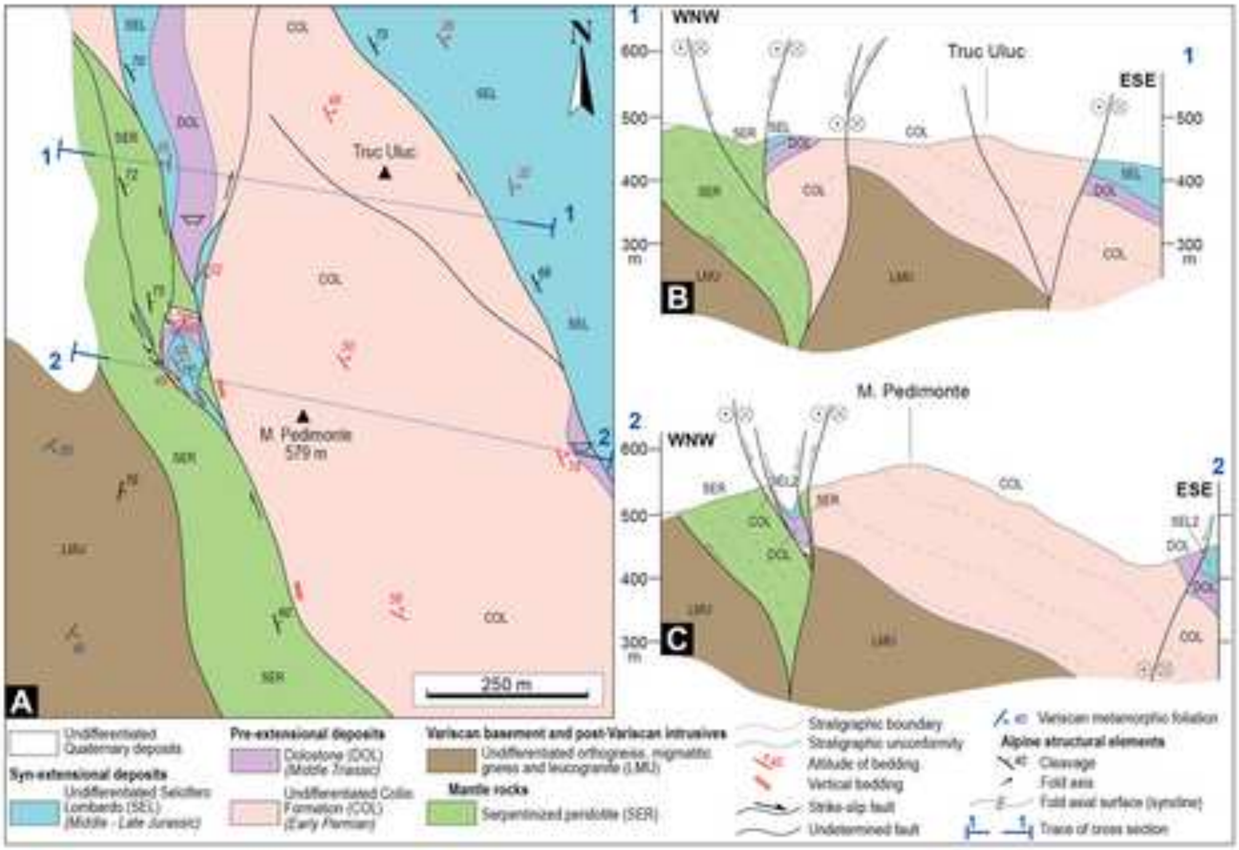

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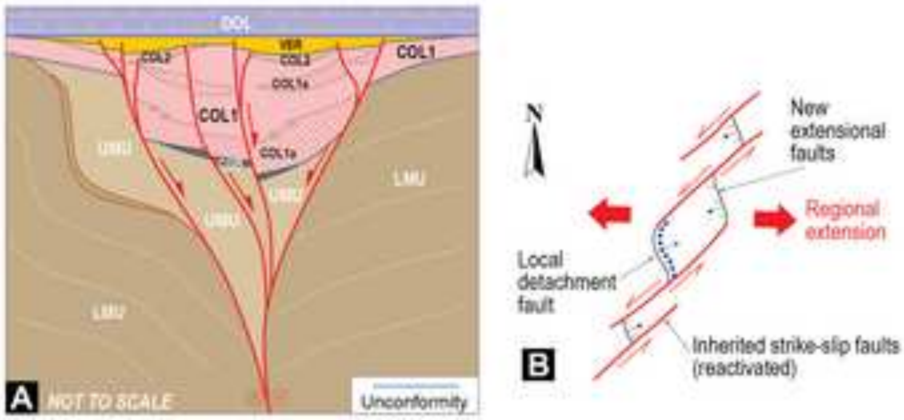

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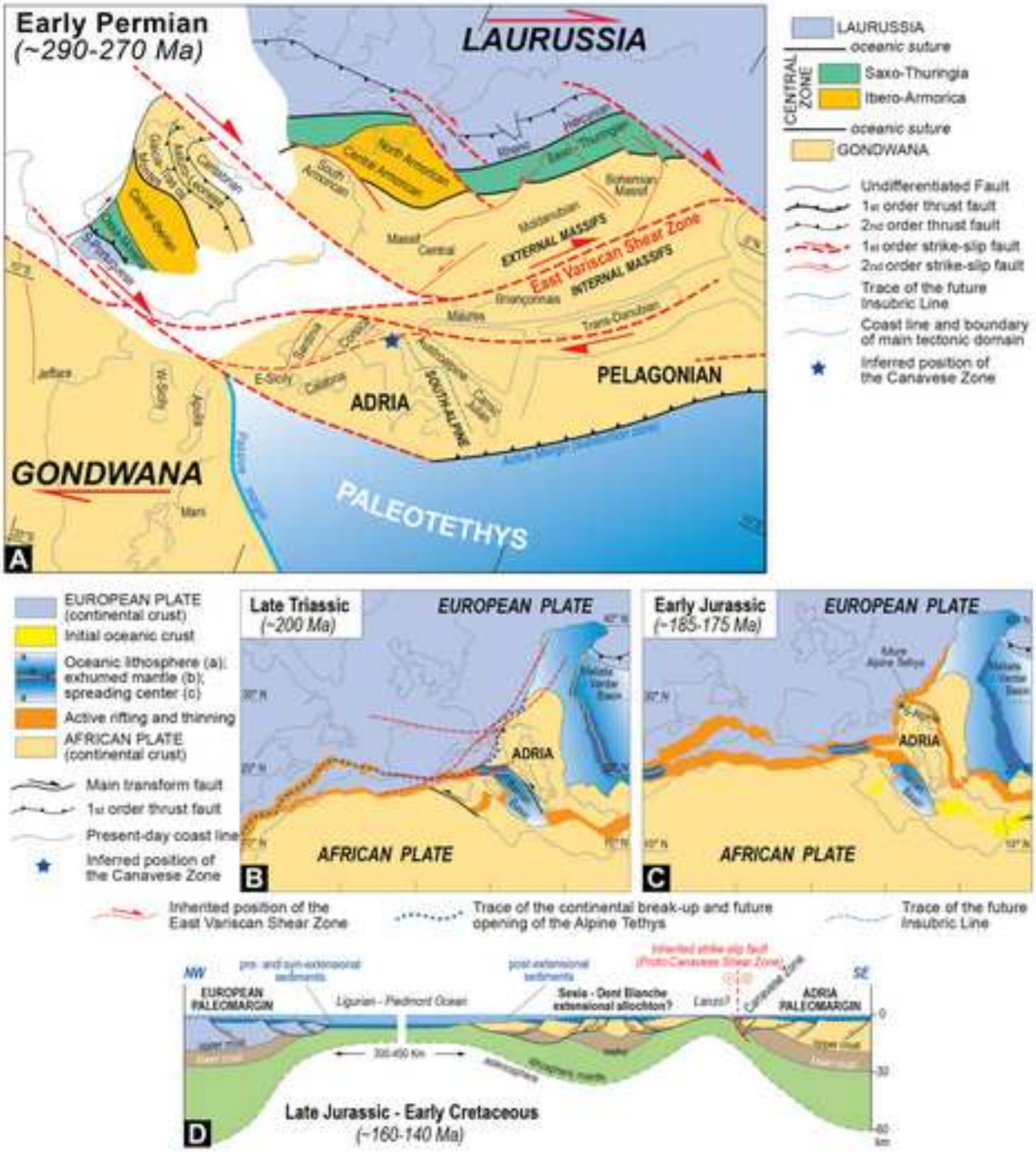

Figure 8 - Festa et al_*Geoscience Frontiers (width 190 mm)*

Figure 9
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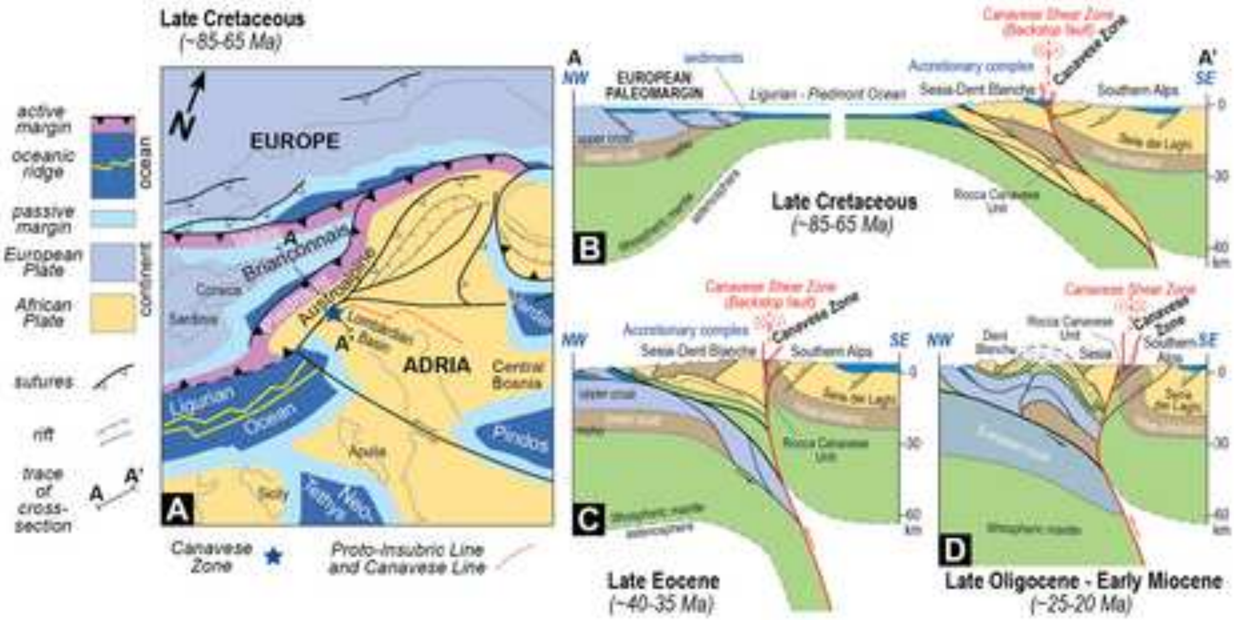

Figure 9 - Festa et al_*Geoscience Frontiers (width 190 mm)*